New Automated Microwave Heating Process for Cooking and Pasteurization of Microwaveable Foods Containing Raw Meats

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ABSTRACT: A new microwave heating process was developed for cooking microwaveable foods containing raw meats. A commercially available inverter-based microwave oven was modified for pasteurization of mechanically tenderized beef, inoculated with *Escherichia coli* O157:H7 (approximately 5 $\log_{10}$ CFU/g) and packaged in a 12-oz CPET tray containing 150-mL de-ionized water. The new microwave heating system was equipped with an infrared sensor and a proportional feedback mechanism to allow temperature controlled microwave heating. A 2-stage heating strategy was adopted to cook the product. In the primary heating stage, the sample surface temperature was increased to an initial temperature set-point (ITSP, 65, 70, 75, or 80 °C). In the secondary heating stage, the heating was continued with a small fraction of microwave power. The effect of ITSP, hold time (0 to 3 min), and sample elevation (0, 0.03, and 0.07 m above turntable) on inactivation of *E. coli* O157:H7 and background microflora was evaluated. It was observed that only a small number (approximately 1.3 logs) of *E. coli* O157:H7 and background microflora were inactivated in the primary heating stage. The elevation 0.07 m, which was in the proximity of the geometric center of the metal cavity, was more effective in inactivating both *E. coli* O157:H7 and background microflora. Substantially more bacteria were inactivated in the secondary heating stage. Complete inactivation of *E. coli* and background microflora was observed with heating at temperatures above 70 °C for more than 1 min. This study demonstrated a new approach for ensuring the safety of microwaveable products containing raw meats.

Keywords: automatic control, *E. coli* O157:H7, inverter, microwave

Introduction

Microwaveable foods are a group of ready-made, prepackaged, frozen, or prechilled products that can be consumed with minimal preparation. Most products are packaged in freezer-safe, heat-stable plastic containers, such as crystalline polyethylene terephthalate (CPTE) trays. For precooked, ready-to-eat products, microwave cooking is a preferred method of food preparation because it can quickly warm the products prior to consumption; however, some products may contain raw meats, particularly raw pork, beef, and poultry meats that are potentially contaminated with foodborne pathogens. Using a microwave oven to cook these products may present a food safety hazard. Since microwave heating is not uniform in nature, food may not be evenly heated in a microwave oven, leaving some parts of the food overcooked and the other parts undercooked. As a result, pathogens in raw meat ingredients may survive after microwave heating, potentially leading to foodborne poisoning.

Several outbreaks of foodborne salmonellosis have been reported in the United States and Canada in connection to the consumption of undercooked microwaveable nonready-to-eat (NRTE) products containing raw or partially cooked poultry meat (MacDougall and others 2004; CDC 2008; Minnesota Dept. of Health 2008; Smith and others 2008; USDA FSIS 2005, 2008). Although Salmonellae are now the primary pathogen currently involved in the outbreaks associated with microwaveable foods, *Escherichia coli* O157:H7 is another major foodborne pathogen that cannot be overlooked. It is definitely a potential contaminant and pathogen of concern if a product contains nonintact raw beef meat as an ingredient. Recognized as a food borne pathogen since the 1980's, *E. coli* O157:H7 is a deadly microorganism of significant concern for public health (Riley and others 1983; Doyle and Schoeni 1984). Although *E. coli* O157:H7 has been detected in various animals, cattle remain the most important reservoir for this microorganism (Buchanan and Doyle 1997; Gansheroff and O'Brien 2000). *E. coli* O157:H7 cells colonize the gastrointestinal tract of cattle and are shed in the feces (Reinstein and others 2007). Therefore, fecal contamination becomes a major route that contributes to foodborne infections associated with *E. coli* O157:H7 (Sargeant and others 2003). As a result, *E. coli* O157H7 is more commonly associated with raw or undercooked foods of bovine origin (Hancock and others 1997; Park and others 1999). Ground beef, a typical raw product made from slaughtered cattle, has caused multiple outbreaks of foodborne poisoning because of undercooking (Vogt and Dippold 2002).

Mechanically tenderized beef meat (MTBM) is a value-added product made from subprimal beef cuts. In a mechanical tenderization process, metal blades or needles are inserted into the less desirable subprimal cuts, disrupting the normal structures of beef muscle (Sutterfield 2007). During the mechanical tenderization process, bacteria, including *E. coli* O157:H7, normally found on the surfaces of beef cuts are translocated into the interior of the meat, causing internal contamination. According to Sporing (1999)

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doi: 10.1111/j.1750-3841.2009.01482.x

THE Society for Food Science & Technology
Journal of Food Science
A Publication of the Institute of Food Technologists

and Luchansky and others (2008), approximately 3% to 4% of *E. coli* O157:H7 inoculated onto meat surfaces can be translocated internally. The internally contaminated MTBM becomes an ideal subject for investigation of microwave heating process in this study.

Temperature-control microwave heating has been used for inactivation of foodborne pathogens. Tong and others (1993) developed a microwave oven with variable continuous power and a feedback temperature controller for heating foods. Welt and others (1993) used the microwave oven developed by Tong and others (1993) for studying reaction kinetics in liquid and semisolid media. Further, Welt and others (1994) used the process to inactivate *Clostridium sporogenes* (PA3679) spores and discovered the inactivation of spores by microwave heating was purely due to thermal effect. While the work reported by Tong and others (1993) and Welt and others (1993, 1994) required physically inserting a thermocouple or a fiber-optic probe directly into samples for process monitoring and control, Huang (2005) used an infrared sensor for remote temperature sensing, and developed a simple computer-controlled microwave heating process for in-package pasteurization of beef frankfurters to eliminate *Listeria monocytogenes*. Later, Huang and Sites (2007) further improved microwave heating process with proportional-integral-derivative (PID) control for better temperature control and inactivation of *L. monocytogenes* in beef frankfurters. All these processes involved in these studies were based on the traditional high voltage transformer technology to provide power to magnetrons. New modern microwave ovens are now equipped with inverter circuits. The inverter microwave oven equipped with high frequency insulated gate bipolar transistor (IGBT) inverter to provide power to magnetrons. Therefore, the research was entirely based on the new inverter technology. No studies have been reported concerning the feasibility of using temperature-controlled inverter-based microwave ovens for inactivation of foodborne pathogens in microwaveable foods.

The objective of this research was to develop a new automated microwave heating process for cooking and pasteurization of microwaveable products that contain raw or partially cooked meats. The goal of this research was to develop an innovative temperature control mechanism to control and optimize the release of microwave energies during microwave heating, while preventing overcooking and nonuniform heating in the products. This project attempted to demonstrate the feasibility of this new microwave heating process for eliminating foodborne pathogens such as *E. coli* O157:H7 and background microflora found naturally in raw beef meat in a simulated microwaveable product.

Materials and Methods

System development

A commercially available inverter-based high power domestic microwave oven (1.25 KW, 2.45 GHz) was selected and modified for this investigation (Figure 1). The internal dimensions of the metal cavity were $0.45 \times 0.42 \times 0.27$ m ($L \times W \times H$). For automated temperature and power control, the original electronic circuit and instrumentation panel were disabled, removed, and retrofitted with a custom-designed PC-based process control module. To improve the uniformity of microwave heating, a mechanical mode stirrer was installed inside the oven and located at the geometric center of the back wall of the metal cavity. The metal blades of the mode stirrer, driven by a synchronous motor, rotated at 34.9 rpm during microwave heating. In combination with the turntable, the mode stirrer was used to improve the temperature uniformity in the test samples by disturbing the wave patterns in the microwave oven.

To measure the surface temperature of the test samples during microwave heating, a calibrated infrared sensor (Model OPTCS10, Optris GmbH, Berlin, Germany) was installed at the geometric center of the top wall of the metal cavity (Figure 1). The diameter of the infrared sensor was 1.2×10^{-2} m, with a D/S (distance to spot diameter) ratio of 10 : 1. During microwave heating, this infrared sensor was used to continuously measure and monitor the surface temperature of samples at the frequency of 1 Hz. The temperature signal was also used for feedback control of microwave power during microwave heating.

The microwave oven was powered by an inverter-based high voltage power supply unit (HV-PSU). The HV-PSU was controlled by a TTL signal to allow continuous control of microwave power. In this study, a 222 Hz TLL signal generated from a digital port of a data acquisition (DAQ) board (Model NI6013, Natl. Instruments Corp., Austin, Tex., U.S.A.), inserted in a PCI slot of an Intel-based personal computer, was used to control the HV-PSU. The interface between the HV−PSU and DAQ board was established using a shielded connector block (Model BNC-2110, Natl. Instruments Corp.). The control of the power level generated by the magnetron was accomplished by adjusting the duty cycle of the TTL signal. The voltage signal from the infrared sensor, corresponding to the surface temperature of a sample, was also interfaced through BNC-2110 and sent to the DAQ board.

Process control

The real-time automatic control of the modified microwave oven was accomplished by a computer program developed using LabView Professional (Version 8.6, Natl. Instruments Corp.). The control program provided a proportional control mechanism to modulate the power output of the magnetron. A 2-stage heating strategy was used for microwave heating. The 1st stage was the primary heating stage, which was designed to increase the surface temperature of a test sample to an initial temperature set-point (ITSP). At this stage, the surface temperature of the sample measured by the infrared sensor was compared with an ITSP to obtain the difference between the 2 values ($\Delta T = T - \text{ITSP}$). A TTL signal, with duty cycles proportional to ΔT, was sent to the HV-PSU to control the power output from the magnetron.

The secondary heating stage started immediately after the sample surface temperature reached an ITSP. Contrary to the conventional wisdom in process control, which usually attempts to control the temperature at a constant value at this stage, the objective of the secondary heating was not to maintain the sample surface temperature constant. Instead, a small amount to microwave energy was provided to allow for continual heating. In the secondary heating stage, a TTL signal with a 5% duty cycle was sent to the HV-PSU to allow the surface temperature of a test sample to slowly increase until a desired target of hold time was achieved. The heating was immediately terminated by cutting off the TTL signal to the microwave oven.

Sample preparation

Beef meat (bottom round roast), purchased from a local butcher shop, was sliced to 0.01 m in thickness, and then tenderized with a handheld meat tenderizer (Model MT-48, Keystone Manufacturing Co. Inc., Buffalo, N.Y., U.S.A.). The needle configurations of the handheld meat tenderizer were identical to commercial blade tenderizers. Meat samples were tenderized in a direction perpendicular to muscle fibers. The tenderized beef meat was further cut into 0.05×0.04 m pieces. After tenderization, the beef samples were transferred to a refrigerator and were inoculated within 30 min. The

samples were designated as mechanically tenderized beef meat, or MTBM.

Preparation of bacterial culture

Three strains (USDA/FSIS 45753-35, 933, and A9218-C1) of *E. coli* O157:H7 were randomly selected from the stock culture collection of USDA, ARS, Eastern Regional Research Center, Wyndmoor, Pa., U.S.A. Each strain was inoculated into 30 mL Brain Heart Infusion Broth (BHI, BD, Sparks, Md., U.S.A.), and incubated at 37 °C overnight with mild shaking. Each culture was harvested by centrifugation (2400 g for 10 min at 4 °C), washed once with 5 mL 0.1% peptone water (PW), recentrifuged, and resuspended in 5 mL PW. A cocktail of the bacteria was formed by combining and mixing the washed bacterial cultures. The cocktail was immediately used to inoculate MTBM samples.

Inoculation of bacteria

MTBM samples, previously kept in a refrigerator, were inoculated with freshly prepared bacterial culture. Each piece was inoculated with 0.1 mL of the bacterial cocktail on both flat surfaces of MTBM and placed in a 12 oz CPET tray (0.13 × 0.10 × 0.03 m, $L \times W \times H$). Four MTBM samples were placed in a CPET tray. After inoculation, the samples were transferred back to the refrigerator (approximately 8 °C) and kept for about 2 h prior to microwave heating. This process allowed the internalization of bacteria.

Calibration of infrared sensor

To use this sensor, 4 fiber-optic probes (SIW-02, Luxtron Corp., Santa Clara, Calif., U.S.A.), each attached to the surface of beef meats facing the infrared sensor in a package covered with a household plastic film. With the turntable disabled, microwave heating was initiated. The surface temperatures of the meat samples were measured and monitored using a fluoroptic thermometer (Model 790, Luxtron Corp., Santa Clara, Calif., U.S.A.). After the surface temperature was above 95 °C, the heating was stopped. After which, signals from both the infrared sensor and the fiber-optic probes were recorded. The average of the 4 readings of the fiber-optic probes was used to represent the surface temperature. The infrared sensor was calibrated with the plastic film to measure the surface temperature of meat samples.

Microwave heating

Immediately prior to heating, 150 mL refrigerated de-ionized water was added to a CPET sample tray. After covering with a household plastic packaging film, each container, with MTBM samples and water, simulating a microwaveable product, was loaded into the microwave oven. The CPET tray was placed directly beneath the infrared sensor, with the sensor pointing vertically at the geometric center of the plastic tray. Only 1 tray was heated for each heating experiment. All experiments were repeated at least 3 times for each heating condition.

Effect of sample elevation on bacterial kill

To evaluate the effect of elevation on thermal inactivation of bacteria, samples were placed at different elevations, corresponding to 0, 0.03, or 0.07 m above the turntable. The samples were 1st heated to 65 °C (ITSP), and remained for additional secondary heating for up to 3 min. After heating, the samples were immediately removed from the microwave oven for recovery of the surviving bacteria. After this experiment, it was observed that the inactivation of *E. coli* O157:H7 was more effective if the samples were placed on a plastic platform 0.07 m above the turntable. From this point forward, therefore, the samples were directly placed on the plastic platform for microwave heating.

Effect of ITSP and hold time on bacterial kill

To evaluate the effect of the surface temperature set-point and hold time on inactivation of bacteria, additional experiments were conducted to increase the surface temperature to an ITSP of 70, 75, or 80 °C, and then hold for 0 to 3 min in the secondary heating stage. After heating, the samples were also immediately removed from the microwave oven for recovery of the surviving bacteria.

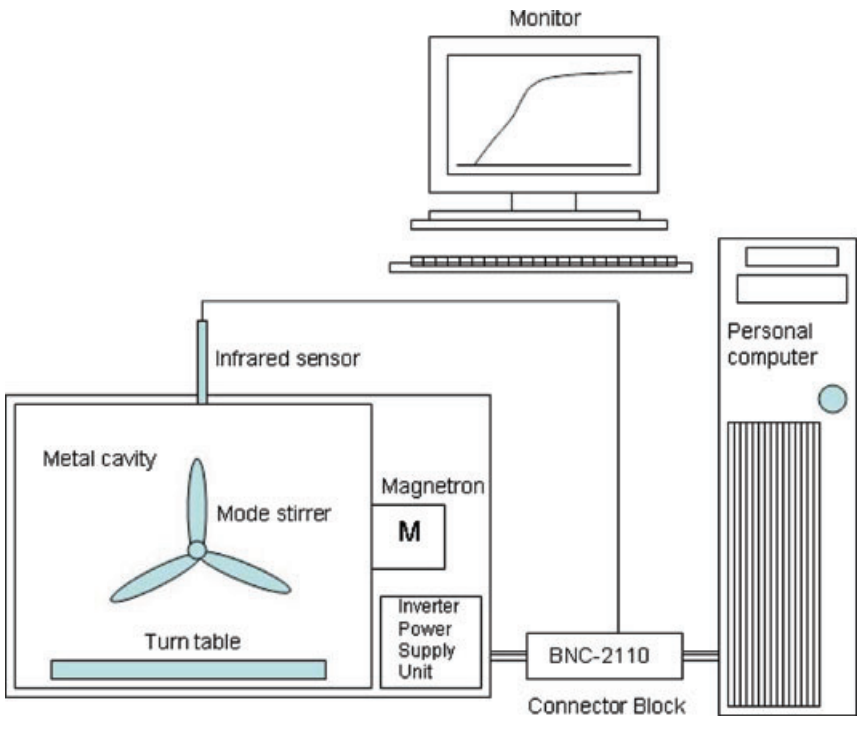

Figure 1 — A modified inverter-based microwave heating apparatus with mode stirrer, infrared sensor, and automatic temperature control system.

Recovery of surviving bacteria

After the sample was removed from the microwave oven, the 4 pieces of MTBM samples were immediately transferred to a filtered stomacher bag containing 200 mL ice-cold 0.1% PW. Each stomacher bag was blended for 2 min in a stomacher (Model Seward Stomacher® 400 Circulator, Bohemia, N.Y., U.S.A.) operated at 260 rpm. An aliquot (0.1 or 1 mL) of the filtered liquid potion in each bag was plated onto 4 tryptic soy agar (TSA, BD, Sparks, Md., U.S.A.) plates, either directly or after serial dilution of 0.1% PW. The TSA plates (per dilution) were maintained at room temperature for 2 h to allow the recovery of heat-injured cells. After which, 2 of the TSA plates were incubated directly at 37 °C overnight to recover the background microflora. The other 2 TSA plates were overlaid with a layer (10 mL) of Sorbitol–MacConkey (SMAC, BD, Sparks, Md., U.S.A.) agar to recover *E. coli* O157:H7. The TSA/SMAC plates were then transferred to a 37 °C incubator and incubated overnight. Since the population of background microflora was 2 orders in magnitude higher than the inoculated *E. coli* O157:H7, the colonies from TSA plates were used to calculate total plate counts (TPC), which were used to represent the population of background microflora. The colonies from TSA/SMAC plates were used to calculate the bacterial counts of the surviving *E. coli* O157:H7. The bacterial counts were converted to $\log_{10}$ CFU/g (colony-forming units per gram of raw meat). If no colonies were observed from TSA/SMAC or TSA plates directly plated with 1 ml undiluted aliquot, the bacterial counts in the samples were treated 0.0 $\log_{10}$ CFU/g in this study. No further enrichment of bacteria was conducted.

Statistical analysis

Analysis of variance (ANOVA) was used to analyze the effect of ITSP in the primary heating stage, hold time in the secondary heating stage, and sample elevation on the inactivation of *E. coli* O157:H7 and background microflora in MTBM samples in CPET trays. The Tukey's studentized range (HSD) test procedure was used to compare and group the means of *E. coli* and TPC counts with respect to each treatment (ITSP, hold time, and elevation). The difference in the means of the surviving bacterial counts was considered statistically significant if $P < 0.05$. The statistical analysis was performed used SAS (Version 9.1, SAS Inst. Inc., Cary, N.C., U.S.A.).

Results and Discussion

Microwave heating and process control

As a test sample was exposed to microwave heating, the electromagnetic energy released from the magnetron to the metal cavity was absorbed, causing its temperature to increase. The change in the surface temperature was monitored by the infrared sensor. Figure 2 illustrates some of the recorded surface temperature histories of the samples in the microwave oven with different ITSPs and hold time. The surface temperature seems to increase almost linearly during the primary heating period. On the average, the temperature increased at a rate of 0.7 ± 0.07 °C/s (mean ± standard deviation, $n = 34$) in this period. After the surface temperature reached a set-point, the heating process entered the 2nd stage. At this stage, the surface continued to increase slowly and at an average rate of 0.06 ± 0.02 °C/s.

The surface temperature fluctuated at every stage of heating, which was probably caused by the uneven temperature distribution on the sample surfaces. The surface temperature variation was easily detected by the infrared sensor as the samples rotated with the turntable. Depending on the hold time in the secondary heating stage, the final surface temperature may be 3 to 10 °C above the ITSP of a process.

The 2-stage heating strategy seemed to work well for this process because the goal was to eliminate bacteria from the samples. With the feedback control mechanism used to adjust the microwave power, it was possible to expose the food to the maximum capacity of the microwave oven, which allowed the temperature to increase at the maximum achievable speed during the primary heating period. As the surface temperature approached an ITSP, the microwave energy was gradually reduced to prevent overcooking. After the secondary heating was initiated, a small amount of microwave energy was provided to continue heating the product, which caused the temperature to increase slowly. This step provided sufficient amount of thermal energy to the test sample, but prevented the product from being overheated. Explosion, usually caused by localized overheating, was prevented in all experiments.

Effect of sample elevation and hold time on thermal inactivation of bacteria

The effect of sample elevation in the microwave oven and hold time on bacterial inactivation was investigated at an ITSP of 65 °C for the primary heating and with hold time up to 3 min for the secondary heating. The average initial concentration of *E. coli* O157:H7 inoculated onto the beef samples was 5 $\log_{10}$ CFU/g, and the average initial population of background microflora, counted as TPC,

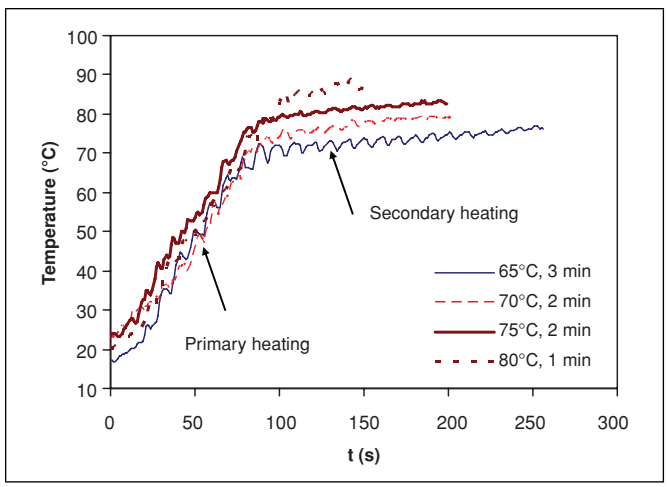

Figure 2—Examples of recorded surface temperature histories during microwave heating, with different ITSPs and hold time.

Table 1—The number of bacteria recovered from samples before and after microwave heating.[a]

Treatment (ITST[b] and secondary heating time)	*E. coli* O157:H7, $\log_{10}$ CFU/g	TPC, $\log_{10}$ CFU/g
Control	5.0 ± 0.3	7.5 ± 0.3
65 °C, 0 min	3.4 ± 0.7	5.7 ± 0.6
65 °C, 1 min	1.3 ± 1.5	4.8 ± 0.3
65 °C, 2 min	0.6 ± 1.1	0.5 ± 1.2
65 °C, 3 min	0.0 ± 0.0	0.0 ± 0.0
70 °C, 0 min	3.4 ± 0.1	4.9 ± 1.1
70 °C, 1 min	0.0 ± 0.0	2.4 ± 1.8
70 °C, 2 min	0.0 ± 0.0	0.0 ± 0.0
75 °C, 0 min	2.9 ± 0.4	4.9 ± 1.0
75 °C, 1 min	0.0 ± 0.0	0.2 ± 0.4
75 °C, 2 min	0.0 ± 0.0	0.0 ± 0.0
80 °C, 0 min	2.5 ± 0.8	4.0 ± 0.7
80 °C, 1 min	0.0 ± 0.0	0.0 ± 0.0

[a]Samples were placed 0.07 m above the turntable.
[b]ITSP.

was 7.5 $\log_{10}$ CFU/g (Table 1). The naturally occurring background microflora population was about 2 orders of magnitude higher than that of the inoculated *E. coli* O157:H7. Therefore, it was possible to differentiate *E. coli* O157:H7 from background microflora with selective media.

After the surface temperature of the samples was increased to 65 °C (corresponding to hold time = 0 min), the mean bacterial population of *E. coli* and background microflora, recovered from all sample locations, was 3.7 and 6.2 $\log_{10}$ CFU/g, respectively (according to Table 2). Averaged from all elevations, the primary heating achieved an average of 1.3 log-reductions in the population of *E. coli* O157:H7 and background microflora.

More bacteria were inactivated as microwave heating progressed in the secondary heating period. The analysis of ANOVA suggested that both secondary heating time (hold time) and sample elevation significantly affected the survival of bacteria during microwave heating ($P < 0.0001$). Tables 1 and 2 list the results of the Tukey's test to differentiate the effect of the secondary heating time and the elevation of samples in the oven on the survival of *E. coli* O157:H7 and background microflora in cooked beef. From Table 2, it is clear that there was no significant difference in the number of bacteria, either *E. coli* or background microflora, recovered from the samples at 0 and 1 min of the secondary heating period. As the secondary heating time was increased beyond 2 min, significantly more bacteria were killed by heat in the microwave oven. This was true for both *E. coli* and background microflora. The results in Table 2 suggested that the secondary heating was critical for the inactivation of bacteria.

The elevation also affected the effectiveness of bacterial inactivation during microwave heating. According to Table 3, there was no significant difference in the survival of bacteria (*E. coli* or background microflora) for the samples placed at 0 and 0.03 m above the turntable. However, for sample placed at 0.07 m above the turntable, significantly fewer survivors were recovered after heating, suggesting that at this elevation level it was more effective in inactivating *E. coli* and background microflora in beef during microwave heating.

The difference in the effectiveness of thermal inactivation for samples placed at different elevations may be attributable to the patterns of microwave radiation in the metal cavity. For samples placed directly on the turntable, microwave energies were distributed above the samples and could only enter the samples from the top direction. For samples located 0.03 m above the turntable, some of the microwave energies were reflected by the bottom metal wall back to the samples. The edges of a package might have received more microwave energy than the center of the package, which might have enhanced the edge heating effect. However, the majority of the sample still received the top-down one-directional microwave exposure. The heating pattern for samples located at this elevation was similar to the one placed directly on the turntable. For samples placed 0.07 cm above the turntable, however, the space between the sample and the bottom metal wall was sufficiently large, allowing more microwave energies to be reflected by the bottom metal wall back to the bottom of a sample. Therefore, the samples were exposed to microwave energies from both the top and bottom directions. Microwave energies could directly penetrate into the samples from all directions, making heating more efficient and uniform in the samples, thus leading to significantly more efficient inactivation of bacteria during microwave heating (Table 3).

Table 2— Analysis (statistical grouping) of the effect of secondary heating time on the survival of bacteria during microwave heating (ITSP = 65 °C). Means with the same superscript in the same column are not significantly different ($\alpha = 0.05$).

Secondary heating time (min)	*E. coli* O157:H7 ($\log_{10}$ CFU/g, $N = 18$)	TPC ($\log_{10}$ CFU/g, $N = 18$)
0	$3.7^{a} \pm 0.6$	$6.2^{a} \pm 0.7$
1	$3.0^{a} \pm 1.2$	$5.5^{a} \pm 1.6$
2	$1.8^{b} \pm 1.4$	$3.5^{b} \pm 2.1$
3	$0.3^{c} \pm 0.9$	$2.2^{c} \pm 2.3$

Table 3— Analysis (statistical grouping) of the effect of sample height on the survival of bacteria during microwave heating (ITSP = 65 °C). Means with the same superscript in the same column are not significantly different ($\alpha = 0.05$).

Sample height (m)	*E. coli* O157:H7 ($\log_{10}$ CFU/g, $N = 24$)	TPC ($\log_{10}$ CFU/g, $N = 24$)
0	$2.5^{a} \pm 1.6$	$5.1^{a} \pm 1.6$
0.03	$2.8^{a} \pm 1.5$	$5.2^{a} \pm 1.8$
0.07	$1.4^{b} \pm 1.6$	$2.8^{b} \pm 1.6$

Effect of ITSP and hold time on inactivation of bacteria

Since previous experimental results had demonstrated that *E. coli* O157:H7 and background microflora were more effectively inactivated if the samples were elevated 0.07 m above the turntable, all the following tests were conducted at this elevation level. According to Table 1, the population of *E. coli* O157:H7 in MTBM was, on the average, reduced by 1.6 log-cycles after the surface temperature reached an ITSP of 65 or 70 °C. As the surface temperature of the samples was increased to an ITSP of 75 or 80 °C, the population of *E. coli* O157:H7 cells were decreased by an average of 2.1 or 2.5 log-cycles. Compared to the initial inoculum level of 5 $\log_{10}$ CFU/g of *E. coli* O157:H7 in MTBM, only a small fraction of *E. coli* was inactivated in the come-up period, or in the primary heating stage. Similar results were also observed with the background microflora in MTBM. Without the secondary heating, only 1.8, 2.6, 2.6, or 3.5 log-cycles in the reduction of background microflora were observed after the surface temperature of the test samples were increased to 65, 70, 75, or 80 °C, respectively. Since the initial concentration of background microflora found in MTBM was very high (7.5 $\log_{10}$ CFU/g), the primary heating was basically ineffective in reducing the background microflora from the test samples.

It is evident now that the majority of the bacterial population survived the initial stage of heating, although the surface temperature of the package might have been increased to a degree lethal to both *E. coli* and background microflora. At the end of the come-up period, the temperature distribution in the beef samples was apparently uneven, as suggested by the color of the meat samples. The edges of the meat samples were apparently cooked, but the center portion remained pink-colored.

The continued heating proved to be critical for eliminating both *E. coli* O157:H7 and background microflora from the test samples, as substantially more bacteria were inactivated at the secondary stage (Table 1). With 3 min secondary heating at 65 °C, or >1 min at temperatures above 70 °C, no survivors, either *E. coli* O157:H7 or background microflora, were found in the samples after heat treatment. At the end of heating, a fiber-optic probe was inserted to meat samples to measure the internal temperature for these test conditions. It was found that the internal temperatures were about the perspective ITSP, sufficiently high to inactivate vegetative cells of microorganisms.

The heating with reduced microwave power in the secondary heating was also critical. With reduced microwave power, the heating could be continued without overcooking the product, thus preventing boiling or explosion from happening. This process allowed elimination of both *E. coli* O157:H7 and background from the simulated product containing MTBM.

Conclusions

The experimental results of this project demonstrated the feasibility of adding a feedback temperature control mechanism to a modern commercial inverter-based domestic high power microwave oven for temperature-controlled microwave heating. With feedback control of the surface temperature, it was possible to design a 2-stage heating processes to eliminate both foodborne pathogens (such as *E. coli* O157:H7) and background microflora from microwaveable products containing meat components. The new microwave heating process made it possible to first rapidly increase the surface temperature of a product in the microwave oven to a set-point and then continue the heating process at a slower pace for an additional 1 to 3 min in the secondary heating period, thus preventing overcooking and internal explosions caused by uncontrolled heating. Due to uneven heating, only a small fraction of inoculated bacteria and background microflora was killed in the come-up period. With sufficient time (< 3 min, depending on temperature), however, all bacteria were eliminated during the secondary heating period. The research clearly demonstrated a new microwave heating process and automatic control strategy to safely prepare microwavable products containing raw meat ingredients.

Acknowledgments

The authors would like to thank Mr. Aaron Williams of USDA, ARS for providing necessary assistance.

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